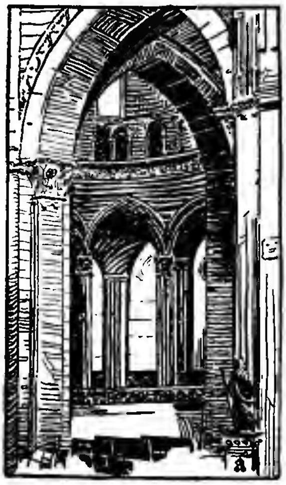
SOUND REFLECTIONS



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FOREWORD

WE are undertaking in "Sound Reflections," to present the accumulated knowledge gained by our Acoustical Engineers in extensive practical experience, together with such other available information on the subject as may be interesting.

Certainly architects are entitled to this information, since it is to their vision and courage that credit is largely due for the development of the Science of Architectural Acoustics to its present usefulness.

We hope it will be helpful; to that end and the encouragement of our purpose, comments, criticisms, suggestions or experiences will find a cordial welcome at all times.

President

ACOUSTICS*

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Its position of importance in every-day life; acoustics formerly a gamble; attacking the subject scientifically; a definite scientific basis established; factors governing acoustics; echo; interference; reverberation; a reverberation problem worked out; wire stretching; other fallacies.

TO the average engineer, the subject of acoustics does not loom large in the every-day matters of a practical world, but when it is realized that it is an important consideration in the design of practically every court room, church, music hall, theatre, auditorium, legislative chamber, bank and even office building, the importance of a knowledge of the subject will be appreciated. Faulty acoustics might be found to be the real reason for the failures of some of the most capable actors, divines and politicians, the world has never had a chance to know. Many a speaker and singer has been severely criticised, thereby suffering considerable loss of prestige, when the fault has been entirely due to the faulty acoustical conditions.

There are thousands of auditoriums in the world that are acoustic nightmares. The late Professor Wallace C. Sabine, of Harvard University, said that the reverberation which accompanies lofty and magnificent architecture increased until even the spoken service became intoned as a Gregorian chant, and that it is not going beyond the bounds of reason to say that in those magnificent churches in Europe, which are housed in magnificent cathedrals, the Catholic, the Lutheran and the Protestant Episcopalian, the form of service is in part determined by the acoustical condition.

Acoustics Formerly a Gamble

In the past, it has been customary in the vast majority of cases to design theatres, churches and auditoriums in general, building them at considerable expense to secure strength, desired seating capacity, noble architectural lines asthetic illumination, wholesome ventilation, etc., and then gamble as to whether the acoustics in the resulting auditorium would be good or bad.

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* Luncheon Address, August 31, 1920, Engineers' Club of Philadelphia.

A Definite Scientific Basis Established

Before 1895 but little definite information was to be obtained by an architect on the subject. He was guided in large measure by his own limited experience or by studies made in existing buildings. The late Professor Wallace C. Sabine, of Harvard University, is to a considerable extent responsible for most of our knowledge on this subject to-day. He began his researches in 1895 and in 1900 published in *The Engineering Record* the results of his five years' work. This was the first real contribution on the subject, and due to the scope of the work and the fact that a mathematical basis was established, the former necessity of chance and guess work was done away with. For eighteen years after the publication of this paper he continued his researches, following the program of investigations there outlined.

The knowledge gained from these researches and from their practical application, augmented by contributions from other physicists, has made it possible to determine from the plans of an auditorium, with a knowledge of the materials of construction, what the acoustical conditions in the finished building will be and to make such changes as might be necessary to overcome faults.

The simplest type of auditorium imaginable is a level plane with a single person as audience. In this case the sound spreads in a hemispherical wave, diminishing in intensity as it increases in size. If instead of one person, there is a large audience, the intensity decreases more rapidly, due to the absorption occasioned by the clothing of the people. The upper part of the sound from the speaker in such an auditorium is entirely lost. The first improvement that suggests itself is to elevate the speaker. The next step is to have the ground or floor sloped so that each row of persons will be slightly elevated. Then, a wall should be placed back of the speaker to reflect that part of the sound towards the audience. We now have the design of the old Greek amphitheatres. With the addition of a roof to prevent the loss of the upper part of the sound waves and the construction of galleries to elevate and bring further front part of the audience, we have the typical form of our modern auditorium.

Factors Governing Acoustics

The size and shape of an auditorium determine the distance traveled by the sound between reflections; while the materials used in the construction determine the loss at each reflection, for which reason it is possible for two rooms designed exactly alike to have entirely different acoustics. An illustration of this is the well-known case of Sanders Theatre in Cambridge and the audit-

orium of the Fogg Art Museum of Harvard College. Sanders Theatre is an old building noted for its good acoustical properties. When the Fogg Art Museum was designed, the architect was instructed to make the auditorium a replica of Sanders Theatre. It was taken for granted that similar design assured similar acoustical conditions. When the auditorium was completed, everyone was greatly surprised to find the acoustics almost impossible. As a result of the development of the subject since that time, the reason for the difference is well known. Sanders Theatre was constructed of comparatively soft materials. All seats were heavily cushioned. The other auditorium was of fire-proof construction. The change produced in the absorbing power of the various surfaces was mainly responsible for the difference in acoustical conditions.

Most people are acquainted with the wonderful acoustical conditions of the Mormon Tabernacle. From an acoustical standpoint the design could not be much worse. However, the building is constructed of wood, which has the highest co-efficient of sound absorption of any building material, and it is due entirely to the presence of so much wood that the acoustics are satisfactory. The shape of the ceiling is responsible for the remarkable echo. A replica of this building with the use of hard materials would result in an acoustical horror.

If a sound be produced in an empty room, having exposed surfaces that are absolutely rigid, it will last almost indefinitely—that is, if we disregard the loss due to the viscosity of the air, which in practical cases is negligible. The sound will travel back and forth from one surface to another, and if the surfaces are absolutely rigid, the original intensity of the sound would be maintained. Of course, no building materials are absolutely rigid. Taking an open window as being totally absorbent, and calling its co-efficient 1.00, Professor Sabine in his researches determined the co-efficient of sound absorption of most of the materials employed in building construction.

The co-efficients of some of the more common materials are given below:

1 square foot each—

Open Window	1.000
Wood sheathing (hard pine)	.061
Plaster on wood lath	.034
Plaster on wire lath	.033
Glass	.027
Plaster on tile	.025
Brick	.025
Concrete	.015
Glazed tile	.01

Following are some miscellaneous co-efficients which are of interest:

1 square foot each—

Carpet	.20
Cheese-cloth	.019
Cork 2.5 centimetres thick, loose on floor	.16

Audience per person	4.7
Hair Felt 1" thick	.53

It is frequently of assistance to compare the reflection of sound waves with the reflection of light waves. A white ceiling will reflect about ninety-five per cent of the light striking it. The same surface painted a dull black will reflect at the most but five per cent of the light. A glazed tile ceiling will reflect ninety-nine per cent of the sound striking it. The same surface covered with one inch of hair felt (the best sound absorber) will only reflect forty-seven per cent of the sound. Increasing the thickness of the felt will further reduce the percentage of sound reflected.

Echo

Echo is a special case of reverberation. Ordinarily the prolongation of a sound after the source has ceased vibrating is continuous until it becomes inaudible. When the sound, instead of being maintained, is short and sharp with a noticeable interval between the direct sound and the reflection, an echo is produced. It is necessary in the case of the average ear for the time interval to be greater than one-twelfth of a second. Professor Watson, of the University of Illinois, in writing about the acoustics of the University Auditorium, mentions an interesting condition that developed during a concert being given by the University orchestra. The number was a xylophone solo with orchestral accompaniment. The echo was so pronounced that at one time the leader of the orchestra beat time to the echo, whereas the players who were immediately around the xylophone kept time to it. Those farther away kept time with the leader, and the resulting confusion can well be imagined.

Curved surfaces should be avoided in the design of an auditorium as far as possible. When used, the center of curvature should be located a considerable distance from the location of seats. The harmful effects produced by a dome, curved ceiling, pendentives, etc., cannot be entirely overcome by acoustical treatment because such surfaces cannot be made totally absorbent. Surfaces covered with felt one inch thick will absorb fifty-three per cent of the sound energy striking it. Forty-seven per cent will still be reflected, which is sometimes sufficient to be a source of complaint.

Interference

So-called "dead" spots in an auditorium are caused by interference. A body in vibration sends off a wave of condensation, which is immediately followed by a wave of rarefaction. As long as the vibration continues, these waves follow each other. Should sound waves traveling by different paths come together again, the condensation wave of one

will meet the condensation wave of another, causing the sound at this place to be re-enforced; or, should one path be slightly shorter than the other so that the condensation wave of one meets the rarefaction wave of the other, there will at this point be no sound.

An interesting example of this phenomenon is the tidal interference observed on the Tongking Peninsula in Asia. The tide of the Pacific Ocean enters the Chinese Sea through two channels. One of these channels is broken up by many small islands, which force the tide in going through to follow a tortuous course, greatly retarding it. The other channel is short, deep and practically unobstructed, causing but little retardation. The tide coming through these two channels produces an effect which varies from place to place. At one port on this peninsula the tide coming from one channel is just six hours later than the tide from the other channel. It is, therefore, high tide from one when it is low tide from the other. As the two tides are equal in size, they neutralize each other so that there is no change in the water level.

Reverberation

Of acoustical defects, the most common is excessive reverberation. A sound produced in a confined space will travel from surface to surface until it is either transmitted by the walls, or is transformed into some other form of energy, generally heat. This process is called absorption. The duration of a sound after the source has ceased vibrating is called reverberation. When the duration of audibility of the standard sound used exceeds the ideal amount, the reverberation is excessive. By using the formula developed by Professor Sabine it is possible readily to determine the reverberation for any room from the plans. From experience I know the desirable reverberation in various sized rooms used for different purposes, and can readily figure by means of the same formula the number of sound absorbing units it is necessary to introduce to obtain this condition.

In the average room used only for speaking, when the volume is approximately 150,000 cubic feet the reverberation under average audience conditions should be not more than 1.9 seconds nor less than 1.3 seconds. For most forms of music it is desirable to have the reverberation exceed 2.1 seconds. When a room is to be used for both speaking and music, it is usual to compromise, having the reverberation slightly excessive for ideal speaking conditions, and slightly less than that demanded for ideal musical conditions. The solution can be varied, of course, to suit the special conditions presented by each case.

As the volume increases it is necessary to increase the dura-

tion of reverberation. Unfortunately, a reduction in the reverberation produces a corresponding reduction in the intensity. For this reason, in a room having a volume of say 400,000 cubic feet, it would not be advisable to reduce the reverberation below 2.7 seconds. This duration of reverberation is slightly excessive for an untrained speaker but necessary to insure sufficient intensity in the furthermost parts of the room.

A Reverberation Problem Worked Out

To illustrate the method of calculating the reverberation and the determining of the area of acoustical treatment required, I will take the case of a court-room, 60′ wide, 100′ long, and 20′ high. The following assumptions are made:

Floor, Concrete.
Side-walls, Plaster on Tile.
Ceiling, Plaster on metal lath.
Area of glass windows, 500 square feet.
450 seats.
Correct conditions desired, when 70 persons are present.

Sabine formula for reverberation is:

$$r = k\frac{V}{a}$$

where "r" equals reverberation in seconds; V equals volume in cubic feet; "a" equals open window units of sound absorption; "k" is a constant and is .05 when foot-second units are used. A sound is used having an intensity of 1,000,000 times the minimum audible intensity and of pitch one octave above Middle "C" on the piano.

Area concrete floor 60′ x 100′ = 6,000 sq. ft.
Co-efficient of absorption of concrete is .015.
6,000 sq. ft. x .015 = *90 units.*
Area side-wall surfaces (60+60+100+100) 20 = 6400 sq. ft.
Area of glass windows = 500 sq. ft.

Net area plaster on hollow tile = 5900 sq. ft.
Co-efficient of plaster on hollow tile is .025.
5900 sq. ft. x .025 = *147.5 units.*
Area of glass 500 sq. ft.; co-efficient .027.
500 sq. ft. x .027 = *13.5 units.*
Area of ceiling 60′ x 100′ = 6,000 sq. ft.
Co-efficient for plaster on wire lath is .033.
6,000 sq. ft. x .033 = *198 units.*
450 seats, co-efficient .1.
450 x .1 = *45 units.*
70 persons, co-efficient 4.7.
The co-efficient for one person is taken at 4.6 due to the fact that the chair occupied by each person has already been considered at .1 and when occupied its value as a sound absorber is almost nothing.
70 persons x 4.6 = *322 units.*
Total number of units, 90+147.5+13.5+198+45+322 = *816.*
Volume of room 60′ x 100′ x 20′ = 120,000 cubic feet.

Substituting in formula $r = k\frac{V}{a}$, the following results are obtained:

$$r = .05 \times \frac{120,000}{816} = 7.34 \text{ seconds.}$$

Experience has shown that the ideal reverberation for a court-room of this size is 1.5 seconds. A reverberation of 7 seconds is

very excessive, and it would be difficult, if not impossible, to hold court in such a room. An increase in the number of persons present will accomplish a reduction in the reverberation due to the additional clothing introduced. The reverberation can readily be determined for all audience conditions.

Substituting 1.5 seconds—the ideal reverberation—for "r" in the formula and solving for "a", we get:

$$1.5 = .05 \times \frac{120{,}000}{a}$$

$$\text{"a"} = 4{,}000.$$

This shows that 4,000 absorptive units are required in the room to have a reverberation of 1.5 seconds. There are 816 units already in the room, so that 4,000 minus 816 equals 3184 additional units which are required. These additional units can be supplied by means of acoustical treatment, which consists of felt, usually one inch in thickness, fastened to certain of the available surfaces of the room. The felt is concealed by tightly stretching a cloth membrane one inch away from it. The cloth is painted or dyed the desired color. Only special paints can be used for this purpose. Each square foot of treatment has a co-efficient of .53. Dividing the number of additional units required, 3184, by the co-efficient of absorption for each square foot of felt, .53, we get the number of square feet of treatment required, namely, 6,007 sq. ft. The ceiling area is 6,000 sq. ft. so that treatment applied to this surface will accomplish the desired results.

Wire Stretching

I am frequently asked regarding the value of stretching wires to overcome acoustical difficulties. The fact that they have been used so extensively misleads most persons into believing that beneficial results can be thereby obtained. There is no theoretical basis for their use and to my knowledge there is no place where any improvement in the acoustics of any auditorium has been brought about by stretching wires in any shape, form or manner.

It is claimed, *e.g.*, that wires radiated from above a speaker's head to parts of the room will assist in carrying the voice to locations where it would otherwise be difficult to hear. A knowledge of the fundamentals of sound enables one to see that this is an impossibility. A wire can only be stretched so as to be in tune with one note. It is, moreover, only possible to impart a microscopic vibration to the wire which is not audible. If the wire were connected in the proper manner to a relatively large sounding board, it would be audible. Even if it were possible to obtain the desired vibration, it would be a decided disadvantage because an undue

prolongation of each sound would be produced. It is desirable in both speech and music to have each sound absorbed quite rapidly so as not to interfere with the proper hearing of succeeding sounds.

Sometimes it is claimed that an echo can be broken up by stretching wires in front of the offending surface. Experience proves this cannot be accomplished. The sound wave, due to its large wave front, passes through the wires with practically no change. The action can be studied by watching an ocean wave pass through a row of piles spaced at various intervals. There is some disturbance noticeable at the piles but a few feet beyond the wave presents a united unbroken front.

The reason for the misunderstanding regarding the use of wires is probably due to the fact that they have been used for years as a means for support and bunting for decorative purposes. An improvement in the acoustics has frequently been noticed and the credit for the change has been given to the wires instead of to the flags and bunting. It is simply the presence of additional sound absorptive materials, placed in usually a particularly desirable location, that causes all sounds to be absorbed more rapidly, thus reducing the period of reverberation or making a surface almost totally absorbent, which otherwise would produce an echo.

I know a court-room where wires were stretched the length of the room and connected with cross wires that were attached to ventilator grills. The clerk of the court told me they thought the undesirable reverberation would be carried by the wires to the ventilators and then out of the room by the current of air. "It seems plausible," he added, "but unfortunately it doesn't work."

Other Fallacies

There are many features of the design of a room that are erroneously blamed for the faulty acoustical conditions. A suspended ceiling, *e.g.*, is thought by some to be set in vibration by the sound waves, thus producing the undesirable reverberation. While making an examination of a council chamber, I was told by the Board in charge that they thought the trouble was produced by the barrel vault ceiling, which due to the suspended construction, was set into vibration by the sound waves. They showed me bags filled with sand which they had placed on top of the ceiling to stop the supposed vibrations. No benefit was obtained. The force of the sound waves produced in this room was actually too feeble to produce even a microscopic vibration. The trouble was due to the use of hard, fire-proof building materials, without the introduction of sufficient sound absorbing materials to neutralize their effect.